博士（環境科学）　佐　藤　　建

学 位 論 文 題 名

Dynamics of the Antarctic ice sheet with coupled ice shelves

（南極氷床変動における棚氷の影響）

学位論文内容の要旨

Antarctica is Earth's southernmost continent, situated almost entirely south of the Antarctic Circle. Except for some coastal regions and high mountains, most of the continent is covered by ice that constitutes the Antarctic ice sheet. The Antarctic ice sheet is the largest land ice mass on the present-day Earth. According to the Fourth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC AR4), the total volume of the ice sheet amounts to approximately 25×10^6 km^3 or 56.6 m SLE (meters of sea level equivalent).

Ice shelves are floating ice bodies that are attached to the margins of an ice sheet. Half of the coastline of the whole Antarctic ice sheet and almost the entire West Antarctic ice sheet are surrounded by ice shelves. Most of the ice flow towards the coast is discharged through them. Recent observations have led to strong concerns that ice-dynamical processes (loss of buttressing from ice shelves, speed-up of ice streams and outlet glaciers) may boost the mass loss and thus lead to an additional contribution to sea level rise. The importance of understanding these processes to assess future sea level change was explicitly recognized in the IPCC AR4.

SICOPOLIS is a dynamic/thermodynamic ice sheet model which has been applied to large ice sheets such as the Greenland, Antarctic, Laurentide and Fennoscandian ice sheets. Although it was applied to the Antarctic ice

sheet, special treatment of ice shelf dynamics has not been included so far. In this study, ice shelf dynamics is considered and coupled with the ice sheet model. The model is applied to the Antarctic ice sheet to study instabilities of the ice sheet related to ice sheet/ice shelf interactions.

Shallow shelf dynamics is applied for the ice shelf model. The performance of the model is tested by using an analytical solution for a two-dimensional ice shelf ramp. The result shows that the model can reproduce the analytical solution with high accuracy. The ice shelf model is then coupled to the ice sheet model SICOPOLIS and applied to the Antarctic ice sheet. Input data are adopted from the SeaRISE project, an international community effort to estimate the contribution of ice sheets to future sea level rise in the next 100s of years. In order to obtain a suitable present-day configuration of the Antarctic ice sheet, it is desirable to carry out a paleoclimatic spin-up over at least a full glacial cycle until the present. The paleoclimatic spin-up is conducted with a fixed-topography approach (the geometry is kept fixed over time, thus not allowed to evolve), while the model is forced by past temperature and accumulation changes estimated by proxies from the Vostok ice core record.

Future climate experiments over 500 years are conducted by using the result of the paleoclimatic spin-up as initial condition. Three types of sensitivity experiments (surface climate, sub-ice-shelf melt rate and basal sliding) are conducted to investigate the key elements for the evolution of the Antarctic ice sheet in a warming climate. Results show that the grounded ice sheet volume reacts most strongly to changes in sub-ice-shelf melt rates. It also decreases with increased basal sliding, although the range is not as large as for sub-ice-shelf melt. The smallest influence is that of direct climate forcing by surface temperature and precipitation. Combination of all the components causes the largest decrease of the ice sheet. The range of grounded ice volume change across all experiments is ~1.3 m SLE after 100 years and ~3.3 m SLE after 500 years. These results show that sea level equivalent change of the Antarctic ice sheet 100 years into the future can be larger than predicted by the IPCC AR4.

学位論文審査の要旨

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In the doctoral thesis of the candidate, an algorithm for solving the dynamic equations of ice shelf flow was developed, and, by matching this solver with the pre-existing shallow ice solver for grounded ice, coupled ice sheet/ice shelf dynamics was implemented in the ice sheet model SICOPOLIS (SImulation COde for POLythermal Ice Sheets). The candidate applied this new version of SICOPOLIS to the Antarctic ice sheet and carried out paleoclimatic simulations from 125,000 years ago until today with the ice topography kept fixed in order to provide suitable initial conditions for future climate runs (spin-up). The suite of future climate runs was conducted over 500 years with the specifications prescribed by the SeaRISE (Sea-level Response to Ice Sheet Evolution) community effort (control run, varied surface climate, varied sub-ice-shelf melt rate, varied basal sliding and several combinations). Selected results obtained at a horizontal resolution of 20 km are discussed in a scientific article (Sato and Greve 2012, *Annals of Glaciology* 53(60), in press), and results at a horizontal resolution of 10 km were submitted to the SeaRISE consortium. The entire work was embedded in the ongoing project "Simulations of the Evolution and Dynamics of the Antarctic Ice Sheet in Past and Future Climates", kindly funded by the Japan Society for the Promotion of Science JSPS under a Grant-in-Aid for Scientific Research A (No. 22244058). The main findings of the thesis can be summarized as follows:

- The fixed-topography spin-up run produced a rather good agreement between measured and modelled surface velocities. A certain trend towards too low simulated values can be attributed to shortcomings of the geothermal heat flux used as input and, possibly, the fixed-topography approach.

- In the future climate experiments, the Antarctic ice sheet reacted most sensitively to changes of the sub-ice-shelf melt rate and second-most sensitively to changes of the basal sliding, while direct climate forcing (by surface temperature and precipitation) showed the smallest influence. This highlights the importance of ice-dynamic processes, as it was explicitly stated in the Fourth IPCC Assessment Report in 2007.
- For the highest model resolution of 10 km, the range of ice volume change across all future climate experiments is ~1.3 metres sea-level equivalent after 100 years and ~3.3 metres sea-level equivalent after 500 years. Hence, the contribution of changes of the Antarctic ice sheet to global sea level rise is potentially larger than projected by the Fourth IPCC Assessment Report.

The four members of the examination committee agreed that the thesis of the candidate constitutes an important step forward in the field of ice sheet modelling. While not entirely new, there are only very few models worldwide, and no other in Japan, that can deal with coupled ice sheet/ice shelf dynamics for three-dimensional and transient real-world systems like the Antarctic ice sheet. This places the new version of SICOPOLIS at the forefront of international ice sheet modelling research. Through a series of community publications currently in preparation, the contribution of the candidate to the international SeaRISE effort (one out of only three with coupled ice sheet/ice shelf dynamics) will serve as input for the Fifth IPCC Assessment Report (to be finalized in 2014) and thus have a significant impact on the consensus predictions of the likely contribution of the Antarctic ice sheet to future sea level rise.

During the three years of the study, the candidate has cooperated actively with domestic as well as international researchers, including a two-month stay at the Bert Bolin Centre for Climate Research (BBCC), Stockholm University, Sweden (hosted by Dr. Nina Kirchner). This highlights the strong linking to the international scientific community he has established. Further, the results have been presented at several domestic (Seppyougakkai Sendai 2010 and Nagaoka 2011, NIPR Symposium 2011) and international (AGU Fall Meetings 2009 and 2010, IGS Symposia Sapporo 2010 and San Diego 2011) conferences, and further publications in international, peer-reviewed scientific journals are on the way.

In the meeting following the examination on April 16, 2012 (Mon), it was unanimously concluded by the four members of the examination committee (the absent member (阿部准教授) delivered a written report) that the candidate's thesis, as well as his performance in the examination, has met the demands to the full satisfaction, and that the candidate is to be conferred the degree of Doctor of Environmental Science [博士 (環境科学)].